

120-year records of spring flows in the Pentland Hills, Midlothian: geological controls and response to drought

Tom Ball^{1*}, Andrew R. Black¹ and Alan M. Macdonald²

¹ School of the Environment, University of Dundee, Perth Road, Dundee DD1 4HN

² British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA

*Email: T.Ball@dundee.ac.uk

Abstract

An archive of hand written operations logs from the former Edinburgh Water Works allows a largely complete record of spring flows to be examined for the 120-year period beginning 1862. The two longest and most consistent records in the archive are for Black Springs, draining an area of talus formed on microgranite and Silurian sediments, and the Bavelaw Springs, which drain the Carboniferous Kinnesswood Formation comprised mostly of sandstones. Weekly flow records are available from 1904, while the 1862–1903 period has monthly data in published form. Auto-Regressive Moving Average Analysis (ARIMA) was used to model the key parameters of the time series. The Black Springs showed a marked variability in flows, indicative of a strong quickflow response superimposed on a baseflow. By contrast, the Bavelaw Springs were much more heavily damped in their response, exhibiting lower within-year and inter-year variability. Recessionary flows were extracted from each record for analysis and comparisons. Results showed consistency in the extended Bavelaw recessions, while those from the Black Springs showed greater variability. The characteristic response of the spring groups will be instructive for water resources modelling and for assessing the effects of climate change on groundwater reserves. Groundwater time series from Scotland's only index well begin only in 1981, while just six in England date back to the 19th century, illustrating the relative paucity of long groundwater records.

Introduction

Spring flow records provide an integrated signal of the effect of rainfall on catchments, providing a test of hydrological response to antecedent conditions over various timescales. The results can assist in validation of climate models, as well as improving the predictive power over future climate and assessing the hydrological response by catchments of different type (Reynard *et al.*, 2010). However, long term spring records require careful pre-screening and quality control, to verify consistency as well as to isolate anthropogenic effects on the catchment, such as those due to land use change and land drainage.

The North Pentland Springs supplied water to Edinburgh from the early 19th century, with around 250 shallow springs harnessed in three major groups (Jardine, 1993; Figure 1). During the mid to late 19th century, several reservoirs were developed by the Edinburgh Water Company (later Edinburgh and District WC) taking both surface runoff and spring flow from the Pentland Hills. The springs remained important for providing baseflow for the reservoirs during dry periods. The increase in storage capacity was augmented with the completion of the Talla Reservoir (1905) and Meggett Reservoir in the early 1980s, located in the Scottish Borders to the south. The springs were thus rendered of minimal importance for supply. However, the historical importance of the Pentland springs is reflected in the meticulous records kept by the Edinburgh and District Water Company (EDWC) from the mid-19th century, which continued, with some gaps, until 1982 (Black, 2003; Black *et al.*, 2006). The records offer the opportunity to understand how spring flows have

responded to rare historic drought episodes. Moreover, they may afford the opportunity to understand this response in a way which allows calibration of models of future response, particularly in the light of modelled climate change predictions.

The objectives of this work were:

- (1) To make available spring flow data in the long records from two of the main Pentland Spring groups (Bavelaw and Black Springs) on timescales from monthly to multi-annual;
- (2) To analyse patterns and identify possible causes of both short term variability and longer term trends, and relate the observed trends to records of climatic change, regionally and locally, over the time period of the record.

Study site

Site description and geology

The Pentland Hills are located near Edinburgh in a zone with a mean annual rainfall of 789 mm (1904–1982, based on daily records from Harlaw reservoir). The spring groups differ in their underlying hydrogeology (Figure 1). The Bavelaw Springs issue from the Kinnesswood formation (widespread in S. Scotland; MacDonald *et al.*, 2005). However, in the Black Springs, the issues occur at the base of a microgranite intrusion with little superficial cover, apart from at the base of the slopes where there are talus and some glacial deposits. Chemistry samples taken from the Black Springs indicate a poorly mineralised groundwater with some evidence of carbonate buffering. It can be interpreted as a mainly shallow groundwater from the granite that has had limited residence

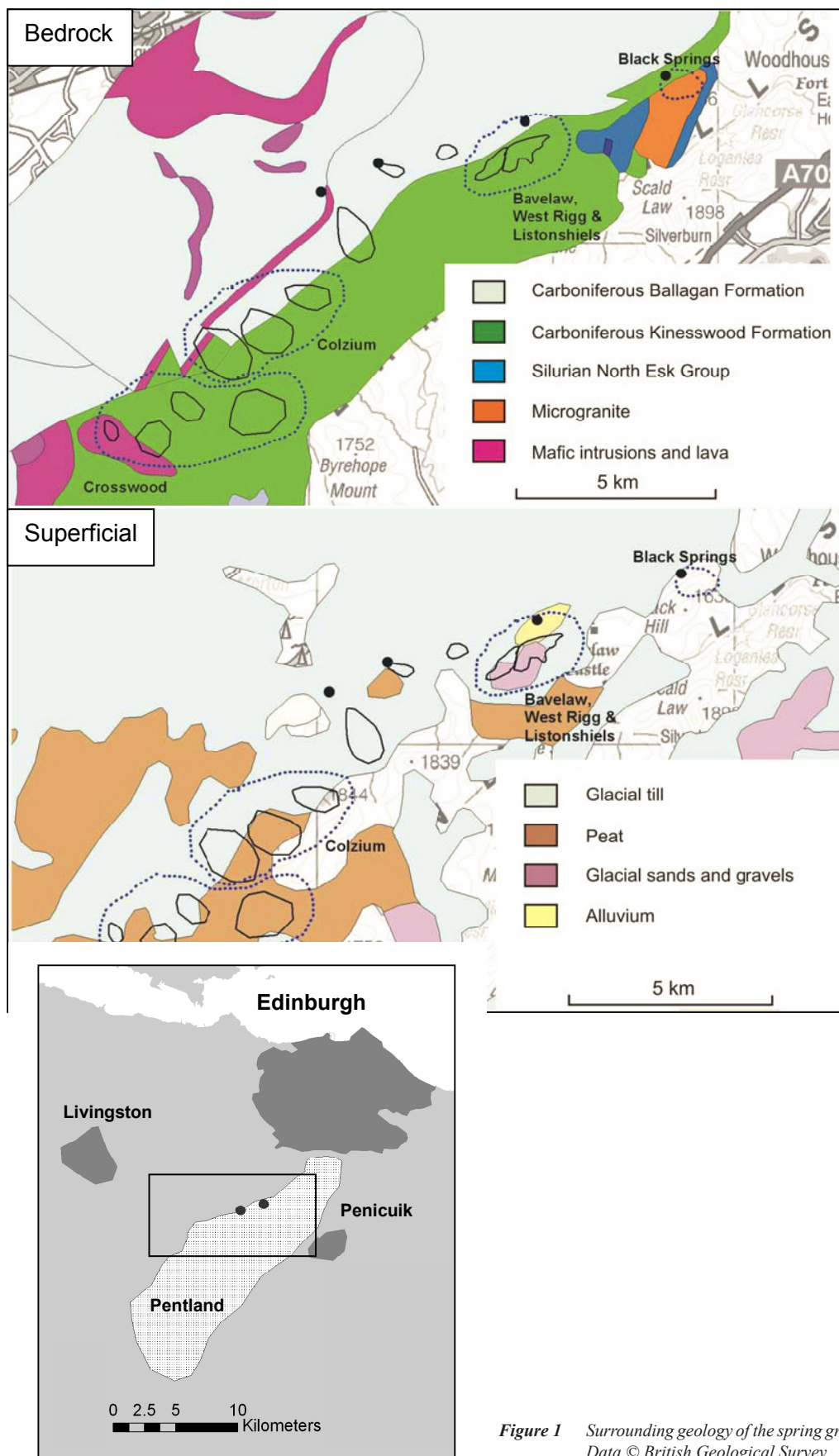


Figure 1 Surrounding geology of the spring groups.
Data © British Geological Survey.

time in either the Kinesswood formation or the overlying superficial deposits. The Bavelaw springs catchment is entirely within the Kinesswood formation with significant thickness of glacial sands and gravels (Figure 1). A single set of chemistry measurements were taken in November 1985 to give a preliminary indication of possible groundwater paths.

The Bavelaw Springs chemistry data are consistent with these springs originating solely from that formation, with lower pH, Ca^{2+} and HCO_3^- concentrations. The Bavelaw spring group was hypothesised to represent the deep groundwater in a high storage aquifer.

Methods

Data capture

The archives of Scottish Water, Farmilehead, Edinburgh, provided weekly readings for spring flow from 1904–1982 with generally minimal gaps. Data from the earlier part of the record (monthly readings, from 1862 to 1904) had previously been published by Tait (1906) in his summary of the Talla reservoir design and construction. Although no information is available on quality control, it is assumed that this was high given the importance of spring flow monitoring to the city's water supply at that time. Data from Jan 1904 were digitised directly from the handwritten records. Log sheets in the records recorded both time taken to fill a stipulated volume at a measuring house, and the flow rate associated with the recorded time, using a look-up table (Black *et al.*, 2006). The measuring houses remained the same over the full record providing good consistency. Weekly readings were averaged to generate monthly figures for the period after 1904, in orders that comparisons could be made with the figures pre-1906. Data gaps were dealt with in the following way. For the monthly dataset, where more than three months were lost from a single year's record, the whole year was omitted from those data analyses that used annual averages. This occurred on only four occasions in each spring group. If up to three months were lost, data were interpolated for the purposes of calculating annual averages, based on an average of the surrounding 30-year period. In practice, this interpolation only needed to be carried out for single missing months.

For climate data, precipitation records were available from Edinburgh Royal Observatory (ERO-Global Historical Climatology Network, 1862–1960) and British Atmospheric Data Centre (UK Met Office, 1960–1982), and Harlaw Reservoir (Scottish Water, 1904–1982). ERO also provided temperature data. It is some 10 km distant from the North Pentland hills and has slightly lower rainfall. Analysis on 1904–1982 data sets always took the Harlaw precipitation data.

Annual mean spring flows for 1904–1982 were initially subjected to double mass analysis (Searcy and Hardison, 1960) against annual total rainfall, to assess any long term change in yield relative to rainfall input. Because of the concerns about the location of the rainfall measurement (see above) and also the lower measurement frequency pre-1904, the data prior to this year were not analysed by this method.

Time series analysis was then conducted on both weekly and monthly data series using Auto-Regressive Integrated Moving Average Analysis [ARIMA(p, d, q)] following Box and Jenkins (1976). This technique has been applied successfully to a number of hydrological phenomena that are inherently autocorrelated in the time domain, including both surface and groundwater related records (Ledolter, 1978; Kallache *et al.*, 2005). Initial analysis revealed both monthly and weekly records at both spring groups had a log-normal distribution, so transformation of the records was carried out before further analysis, following Ledolter (1976). Model identification then progressed iteratively from an analysis of autocorrelation structures. Seasonal multiplicative models [$(p, d, q)(P, D, Q)z$] were identified based on both monthly ($z=12$) and weekly ($z=52$) records. For years in which 53 weeks of records occurred, the average of week 52 and 53 was taken.

A further stage in the analysis was to compare the weekly spring flow record to the Harlaw precipitation record for the period 1904–82 when precipitation data were available at Harlaw. Linear regression models were used for this analysis, aggregating and lagging the weekly recorded precipitation data at several levels to find the optimal fit between data sets.

Results

Double mass analysis

Double mass plots (Figure 2), show increases in integrated rainfall occurring at a similar rate to integrated flow; both plots show a straight line for almost the entire period. A kink in the mid-1970s appears in both plots at the same time and so is either the result of a change in rainfall recording or some unknown change in the catchment which is common to both groups. The fact that the observed trends are very similar between the spring groups across the whole record, in spite of their different overall flow magnitudes, tend to indicate that the cause was extraneous and at least regional in nature. There is, therefore, a consistency of response which supports meaningful analysis of the recorded flows.

Variability of flow

Flow duration curves based on the weekly measurements showed substantial differences between the spring groups

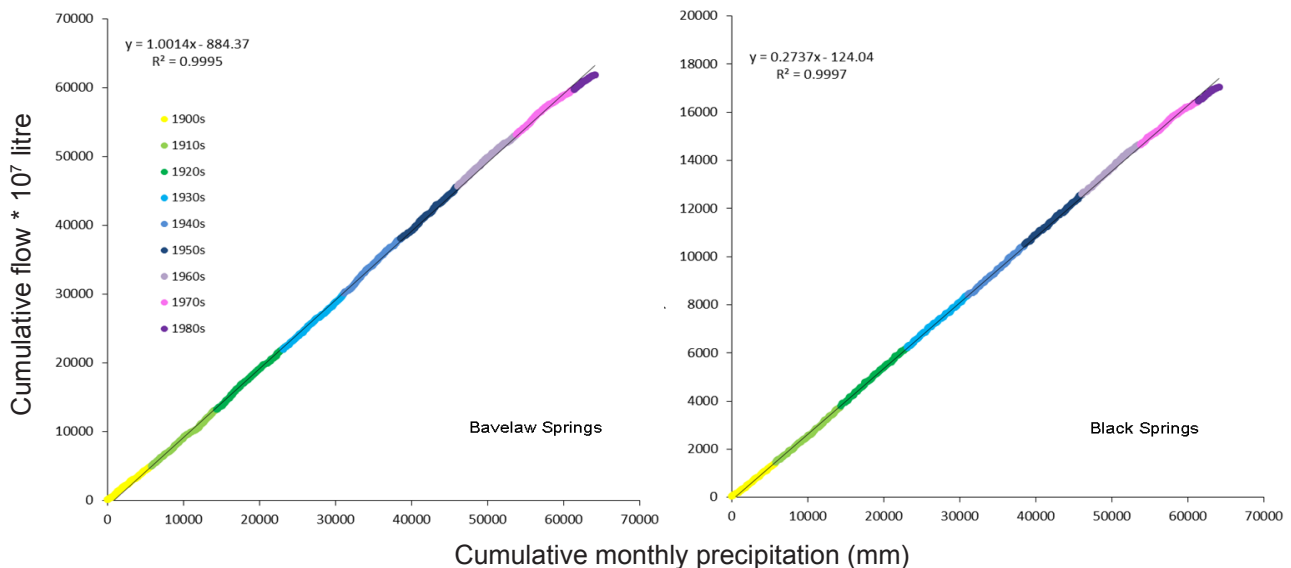


Figure 2 Double mass plots showing relationship between cumulative flow and cumulative precipitation for the spring groups. Precipitation data are taken from Harlaw reservoir (1904-1982 record)

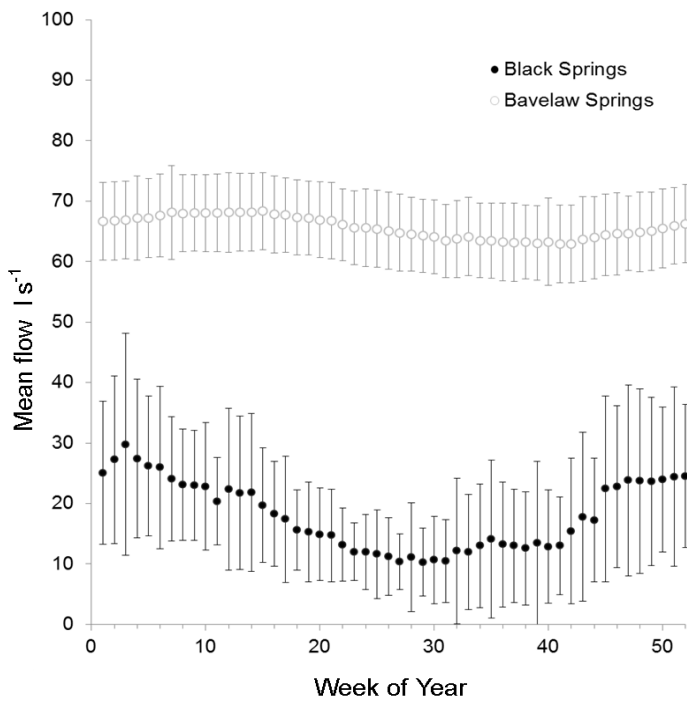


Figure 3 Mean flow (measured weekly) and standard deviation across the full record for which weekly flows available (1904–1982)

(Figure 3), with the Black Springs showing more variability and a faster response to rainfall input, as expected given their water geochemistry.

Time series analysis of monthly (1862–1982) and weekly (1904–1982) flows shows data structures with a variety of levels of variation (Figure 4; Table 1). For the monthly records, the Bavelaw Springs showed nonstationarity on both a weekly and seasonal (period 12) basis, requiring differencing. However, on a seasonal (period 52 basis), using the weekly data, the data trend was stationary. The Black Springs showed the same autoregressive structure in the time series models for both the short term and seasonal components. It is noteworthy that both monthly and weekly models for the Black Springs showed stationarity on a short term basis, with no differencing term needed, but, like the Bavelaw springs, nonstationarity on a seasonal basis (differencing term = 1: Table 1). The Bavelaw monthly data were explained mainly by moving average parameters; indeed, for the seasonal (period 12) model, no autoregressive components needed to be included to develop a model. On a weekly level, however, autoregressive parameters were significant.

Table 1 ARIMA Time series parameters for trend lines fitted to the monthly flow readings from the two spring groups (log-transformed prior to analysis)

Spring Group	Seasonal Time Series Model	Parameters		R ²	P
Bavelaw Springs	Monthly 1862-1982 ARIMA(0,1,1)(0,1,1)	Constant MA _{lag 1} MA _{seasonal 12}	-1.77*10 ⁻⁵ 0.258 (.03) 0.994 (.07)	0.453	Ljung -Box Q 0.142 0.381 <0.001 <0.001
	Weekly 1904-1982 ARIMA(1,1,1)(1,0,1)	Constant AR _{lag 1} AR _{seasonal 52} MA _{seasonal 52}	-2.89*10 ⁻⁵ 0.188 (.03) -0.660 (.30) 0.618 (.03)	0.899	Ljung -Box Q 0.156 0.790 <0.001 0.028 <0.001
Black Springs	Monthly 1862-1982 ARIMA(1,0,0)(0,1,1)	Constant AR _{lag 1} MA _{seasonal 12}	-0.001 (.01) 0.560 (.02) 0.988 (.02)	0.607	Ljung -Box Q 0.107 0.002 <0.001 <0.001
	Weekly 1904-1982 ARIMA(1,0,0)(0,1,1)	Constant AR _{lag 1} MA _{seasonal 52}	-0.002 (.01) 0.814 (.01) 0.978 (.02)	0.807	Ljung -Box Q 0.131 0.007 <0.001 <0.001

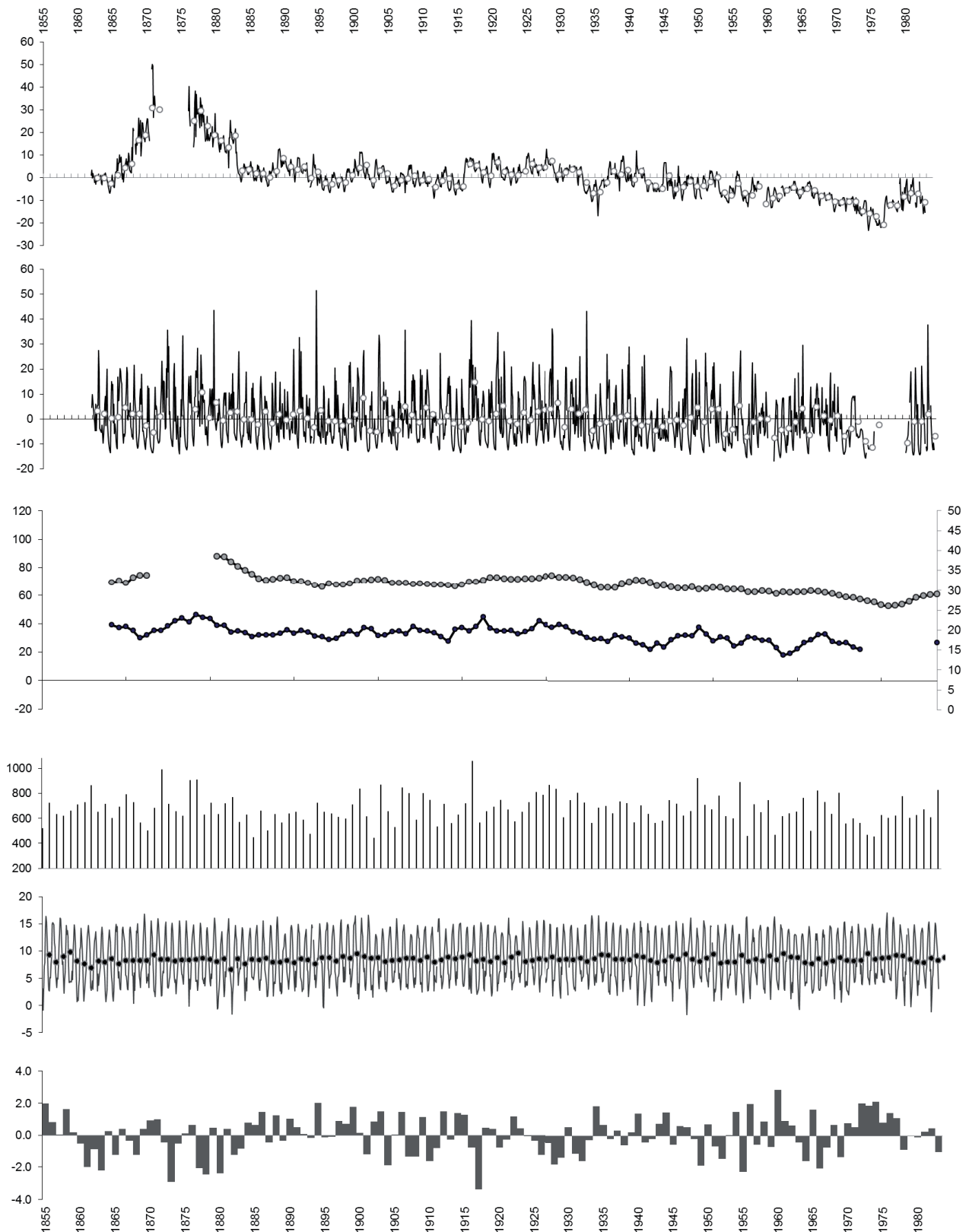


Figure 4 Full data records of monthly flows from the Bavelaw Springs and Black Springs and climate data 1862-1982. Temperature and precipitation data are taken from Edinburgh Royal Observatory (Global Historical Climatology Network). Fitted lines represent linear fits to the record as described in text and Table 1. The aridity index (bottom panel) is calculated as described in Marsh *et al.* (2006): standardised precipitation + {0.5 * standardised temperature

Extreme low flows

Low flows

A low flow spring flow event results from a combination of unusually low recharge and high evapotranspiration rates during summer, and low winter recharge (Marsh *et al.*, 2006), interacting with the inherent recharge characteristics

of the spring in question. With the knowledge gained from the above flow analysis it was hypothesised that the more buffered spring group (Bavelaw) would show more resilience to short term declines in recharge. Two low flow periods were analysed in more detail (full weekly data) to assess the resilience of flow; 1954–5 and 1959–61. During drought periods, yields from the Black Springs typically decline to

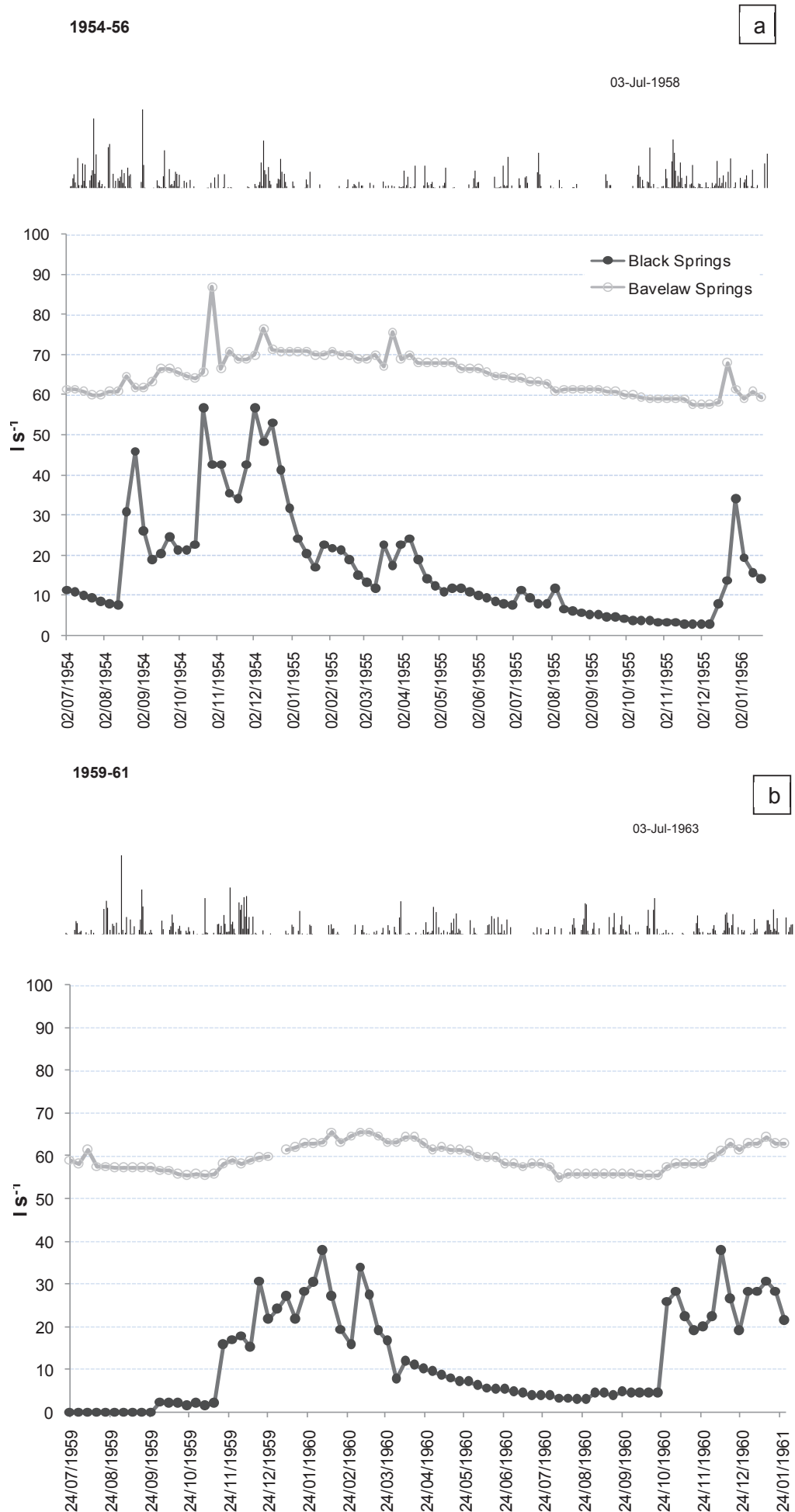


Figure 5 Spring flow records and daily precipitation during the (a) 1954-1956 drought and (b) 1958-59 drought. Precipitation data are taken from Harlaw Reservoir.

2–3 ls^{-1} while at the Bavelaw group that the decline is, in absolute terms, low, flow remaining at around 55–60 ls^{-1} . According to the aridity index (applied to southern England drought data by Marsh *et al.*, 2006) both these periods were high aridity, with indices of 2.0 and 2.9 respectively based on the local climate data from Harlaw/ ERO.

The charts of weekly flow and rainfall during some selected low flow events (Figure 5) illustrate the greater buffering of the Bavelaw springs in the face of low rainfall inputs. In the runup to the 1954–56 drought, the low rainfall input in the later part of the preceding winter (from late Jan) and spring is evident. During an initial period in late winter when flow was supported by rainfall received the previous autumn, a ‘double dip’ in rainfall occurred. This caused a substantial decline in mean flow for both spring groups, more dramatic in the Black Springs group. At the Bavelaw springs, the flow appears to have been less variable and more resilient in the face of declining rainfall in the event.

The 1959–61 drought was again traceable to low winter recharge evident on Figure 5, exacerbated by dry spells in the following summers. However, the Bavelaw groups barely registers any decline until the latter part of this period, into April 1960. The Black Springs rebound more slowly than Bavelaw following the end of this dry period.

Further work

Useful further investigation will include analysis of the correspondence of the series with other long term records for this part of Scotland, notably the record of the Leven sluices by Sargent and Ledger (1992). It is then planned to include process based hydrological modelling of flows that incorporates the effect of evapotranspiration, which could add to existing land surface parameterisation techniques in climate modelling. It would be of great value for such modelling to re-start measurements from these groups following the previous protocols. For application of results to the future, the springs must be maintained to the condition that they had up to the 1980s/90s, at which point maintenance activities were abandoned. Further use of the data could be made for an assessment of recharge rates of reservoirs in the catchments from groundwater (Black and Cranston, 1999).

Conclusions

Analysis of temporal flow data from the Pentland springs has shown the data set to reflect response to climatic variables driven by precipitation in the short term to a contrasting degree based on underlying geology. There is tentative evidence of long term trends. A full transfer function model is desirable to deepen understanding of the subsurface reservoirs and flows. It would be of great interest to resample these springs to see whether, 30 years after records ceased, there have been any significant shifts in stream flow averages and response.

Acknowledgments

We gratefully acknowledge the help of Scottish Water at Fairmilehead, Edinburgh, for providing access to the records, and to the Scottish Environment Protection Agency and the British Geological Survey for co-funding this work.

References

- Box, G.E.P, Jenkins, G.M. and Reinsel, G.C. 1976. *Time series analysis: Forecasting and control*.
- Black, A.R. 2003. Pentland Springs – an untapped store of knowledge. Abstract of paper presented to joint meeting of the Hydrogeology group of the Geological Society of London and the Scottish Hydrological Group, November 2003, Stirling. http://www.geolsoc.org.uk/template.cfm?name=Groundwater_in_Scotland.
- Black, A.R., MacDonald, A.M. and, Ball T. 2006. Assessing the value of historic spring flow records in Scotland. A study focusing on the North Pentland Springs. Report to Scottish Environment Protection Agency, March 2006. www.sepa.org.uk/science_and_research/publications.aspx
- Black, A.R. and Cranston, M.D. 1999. Derivation of an 88-year inflow record for Talla Reservoir, Scotland, with special reference to low flows. *J.CIWEM*, **13**, 423–429.
- Jardine, R.W. 1993. James Jardine and the Edinburgh Water Company. *Newcomen Soc. Trans.*, **64**, 121–129.
- Kallache, M., Rust, H.W. and Kroop, J. 2005. Trend assessment: applications for hydrology and climate research. *Nonlin. Proc. Geoph.*, **12**, 201–210.
- Ledolter, J. 1976. *ARIMA models and their use in modelling hydrologic sequences*. Research Memorandum, International Institute for Supplied Systems Analysis, USA.
- Ledolter, J. 1978. The analysis of multivariate time series applied to problems in hydrology. *J. Hydrol.*, **36**, 327–352.
- MacDonald, A.M., Robins, N.S., Ball, D.F. and Ó Dochartaigh, B.É. 2005. An overview of groundwater in Scotland. *Scot. J. Geol.*, **41**, 3–11.
- Marsh, T.J. 2004. The UK drought of 2003: a hydrological review. *Weather*, **59**, 224–230.
- Marsh, T.M., Cole, G. and Wilby, R. 2006. Major droughts in England and Wales, 1800–2006. *Weather*, **62**, 87–93.
- Reynard, N.S., Crooks, S., Kay, A.L. and Prudhomme, C. 2010. *Regionalised impacts of climate change on flood flows*. R and D Technical Report FD2020/ TR. Dept for Environment and Rural Affairs, London.
- Sargent, R.J. and Ledger, D.C. 1992. Derivation of a 130 year run-off record from sluice records for the Loch Leven catchment, south-east Scotland. *Proc. Inst. Civ. Eng. Wat. Marit.*, **96**
- Searcy, J.K. and Hardison, C.H. 1960. *Double mass curves*. U.S. Geological Survey Water Supply Paper 1541-B.
- Tait, W.A.P. 1906. The Talla water-supply of the Edinburgh and District Waterworks. *Mins. Proc. Inst. Civ. Eng.*, **167**, 102–152.